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Climate proofing island energy infrastructure systems: Framing resilience based policy interventions

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ABSTRACT

One of the most discernible impacts of climate change is the increasing severity and unpredictability of extreme weather conditions. Small island developing states are particularly vulnerable to these conditions, with one of the impacts being on energy supplies due to damaging energy infrastructure, resulting in power outages and economic losses. Drawing on resilience theory to frame the discourse, we present an updated overview of how island energy infrastructures have been and continue to be negatively impacted. This same framework also provides a lens through which we identify the challenges involved in recovery, rebuilding and returning energy security in these contexts.

1. Introduction

Small Island Developing States (SIDS) are a group of developing countries facing specific but also similar environmental and economic challenges. SIDS are small, remote and isolated states disconnected to the main continent with limited resources which make them more vulnerable (Wolf et al., 2016). SIDS are geographically located in three distinct regions namely in the AIMS (Africa, Indian Ocean, Mediterranean and South China Sea), Caribbean and Pacific, with a significant number of them located in the Caribbean and South Pacific regions (Surroop et al., 2018). There are 37 SIDS that are UN members in the three regions. The land-to-sea ratios for the SIDS are huge such that in many cases, the Exclusive Economic Zones (EEZs) are larger than the land area. The EEZ for Samoa, for example, is eight times the land surface area.

Most of the SIDS depend heavily on fossil fuels which is used for power generation and transportation. Some SIDS like Trinidad and Tobago and Papua New Guinea (PNG) produce and export fossil fuels. Though renewable energy is present in the form of biomass (bagasse), hydropower, solar, wind; they are only a limited percentage of their energy mix except in countries like Fiji where there is significant amount of hydropower. However, solar water heater is very popular in SIDS since they are blessed by a good solar regime.

All countries are facing the climate change effect, however given that SIDS are surrounded by the ocean make them more vulnerable to the effect of climate change although they are the ones contributing less in terms of greenhouse gases emissions. Irrespective of the geographical location of the SIDS, they are all vulnerable to extreme weather conditions like tropical storms, cyclones and hurricanes, severe droughts, flooding, flash flood, rising sea levels and other weather-related phenomena. The extreme weather conditions which are becoming more frequent are affecting the SIDS negatively. In many cases, the energy infrastructure has been badly affected where a major portion of the islanders are deprived from the supply of electricity (Shah et al., 2016).

When viewed through the lens of resilience theory, the question becomes one of investigating nature of how the human, natural and physical infrastructure elements that interact in such intimate and limited conditions of small island developing states, can be handled when opposed to climate induced disturbances and uncertainty. Furthermore, while it can be well acknowledged that resilient infrastructure, energy and otherwise, is a preoccupation of the engineering sciences (Kennedy and Corfee-Morlot, 2013; O'Rourke, 2007), here we attempt to pull this into the realm of possible policy level prescriptions that would meaningfully support efforts in SIDS. Data were collected on various SIDS on their demographic, energy consumption, impact on the energy infrastructure. The data were assessed to come up with climate resilience-based policy for energy infrastructure.

Section 2 of this article provides an overview on the energy profile and the demographic situation of SIDS. Section 3 presents views on resilience theory and in section 4, the theoretical lens is applied to highlight the impacts of different extreme weather conditions in the different geographically located SIDS. Section 5 then provides a

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Table 1
Population, land area and GDP of SIDS.
Source: World Bank, 2017a

SIDS	Population	Land Area (km^2)	GDP (USD million)
Antigua and Barbuda	92000	440	1300
Bahamas	388000	10000	8900
Barbados	284000	430	4400
Belize	359000	23000	1800
Cape Verde	521000	4000	1600
Comoros	788000	1900	565
Cuba	11400000	104000	87100
Dominica	73000	750	517
Dominican Republic	10500000	48000	68100
Federated States of Micronesia	104000	700	315
Fiji	892000	18000	4400
Grenada	107000	340	984
Guinea-Bissau	1800000	28000	1100
Guyana	767000	197000	3200
Haiti	10700000	28000	8800
Jamaica	2800000	11000	14300
Kiribati	112000	810	160
Maldives	409000	300	3400
Marshall Islands	53000	180	179
Mauritius	1300000	2000	11700
Nauru	12000	20	100.5
Palau	21000	460	287
PNG	7600000	453000	16900
Samoa	193000	2800	761
São T & P	190000	960	317.7
Seychelles	93000	460	1400
Singapore	5500000	709	292700
Solomon Islands	584000	28000	1100
St Kitts and Nevis	56000	260	876
St Lucia	185000	610	1400
St Vincent & Grenadines	109000	390	737
Suriname	543000	156000	5200
Timor-Leste	1200000	1000	1400
Tonga	106000	720	435
Trinidad and Tobago	1400000	5100	23600
Tuvalu	10000	30	32.7
Vanuatu	265000	12000	742

discussion of the current situation in SIDS, highlighting some of the actions taken towards increasing the resilience of the energy infrastructure in these small islands. Section 6 draws from that discussion to provide a resiliency-based framework of policy level approaches to consider. Lastly, section 7 suggests how this study contributes to advancing policy action that supports practical implementation.

2. Energy profile

2.1. Demographics

SIDS are generally small expect for few of them, however, they are diverse from each other in terms of population size and Gross Domestic Product (GDP). The land surface area varies considerably from Nauru, the smallest island with a surface area of 20 km^2 and a total population of 12000 to PNG with a surface area of 453000 km^2 and a population of 7.6 million as shown in Table 1. Since Singapore is very developed, it has the highest GDP of 292700 million USD and Tuvalu has the lowest GDP of 32.7 million USD.

The variation in population and size of the islands lead to very different population densities. Singapore, for example, has a total population of 5.5 million over a surface area of 709 km^2 which makes it the most densely populated SIDS. It has a population density of 7757 people per km^2 followed by Maldives and Timor-Leste. Surinam and Guyana are the least densely populated with a population density of 3 and 4 people/km^2 respectively as shown in Fig. 1.

2.2. Energy consumption

Energy access and security is one of the big challenges in SIDS. SIDS are mostly heavily dependent on fossil fuels. The purchase cost of fossil fuels is very high due to the remoteness and old infrastructure of the islands. In fact, many SIDS spend a significant share of their national budgets on importing fossil fuels and in some cases the same amount, if not more, is spent in addressing the negative impact of climate change in their respective jurisdiction (Shah and Niles, 2016).

The energy consumption varies between SIDS and this is mainly due to the affordability of energy. Many SIDS cannot afford to provide energy access to all the population due to the high cost of energy. Moreover, some SIDS cannot afford or are very slow in terms of economic development and in the absence of economic development the wealth of the country cannot improve. As such, the energy consumption per capita is very low. As observed in Fig. 2, Timor-Leste has the lowest energy use per capita with a consumption of 60 kg oil equivalent followed by Guinea-Bissau and Comoros with an energy consumption of 64 and 65 kg oil equivalent respectively. Trinidad and Tobago has the highest energy consumption per capita which corresponds to 14447 kg oil equivalent followed by Singapore with 5122 kg oil equivalent.

Timilsina and Shah (2016) stated that the energy consumption per capita is above 4877 kg oil equivalent for high income countries, below 4877 and above 1283 kg oil equivalent for middle income countries and above 359 kg oil equivalent for low income countries. If these criteria are used, Timor-Leste, Guinea-Bissau, Comoros, Kiribati, Solomon Islands, Vanuatu, Cape Verde, São Tome & Principe and Samoa are below low income countries, Haiti, Tonga, Dominica, Marshall Islands, Belize, Fiji, St Vincent & Grenadines, Guyana, Dominican Republic, St Lucia, Grenada, Maldives, Jamaica, Cuba, Mauritius and Suriname are below middle income countries, Barbados, St Kitts and Nevis, Antigua and Barbuda, Bahamas and Seychelles are middle income countries and Singapore and Trinidad and Tobago are high income countries only from an energy consumption perspectives.

2.3. Installed capacity

Electricity is produced from different sources namely, oil, coal, biomass, hydro, solar, wind among others. However, fossil fuels remain the dominating one in most SIDS. Electricity is produced either by the state-owned power plants or independent power producers. The power transmission and distribution is done by the utility companies which are mostly owned by the Government, however, in some cases, it is public and private partnership. The total installed capacity is depended on the affordability and the level of development of the country. Countries that are developed have a better installed capacity and transmission and distribution with a high percentage of access to energy. The highest installed capacity is in Singapore which has a GDP of 292700 million USD with a total installed capacity of 10.7 GW and is the most developed SIDS while there are five other countries that have installation capacities of more than 1 GW namely Jamaica – 1.2 GW, Trinidad and Tobago – 1.43 GW, Dominican Republic – 3 GW, Cuba – 5.5 GW, and Singapore - 10.7 GW. Tuvalu has the lowest installed capacity – 3.9 MW followed by Nauru – 4.9 MW and Kiribati – 5.8 MW as observed in Fig. 3.

3. Theoretical foundation: resilience theory

While the original conceptualization of resiliency of systems is not new and has been a fundamental focus of study and application across fields grounded in the discipline of physics for near a century, it is only more recently that scholars in the natural and social sciences have come to consider how resilient systems resemble (or not) ecological and sociological dynamics. By the mid-2000's with the increasingly urgent scientific reportings of world bodies such as the IPCC, on the status of global warming and how this phenomena is both impacted by and

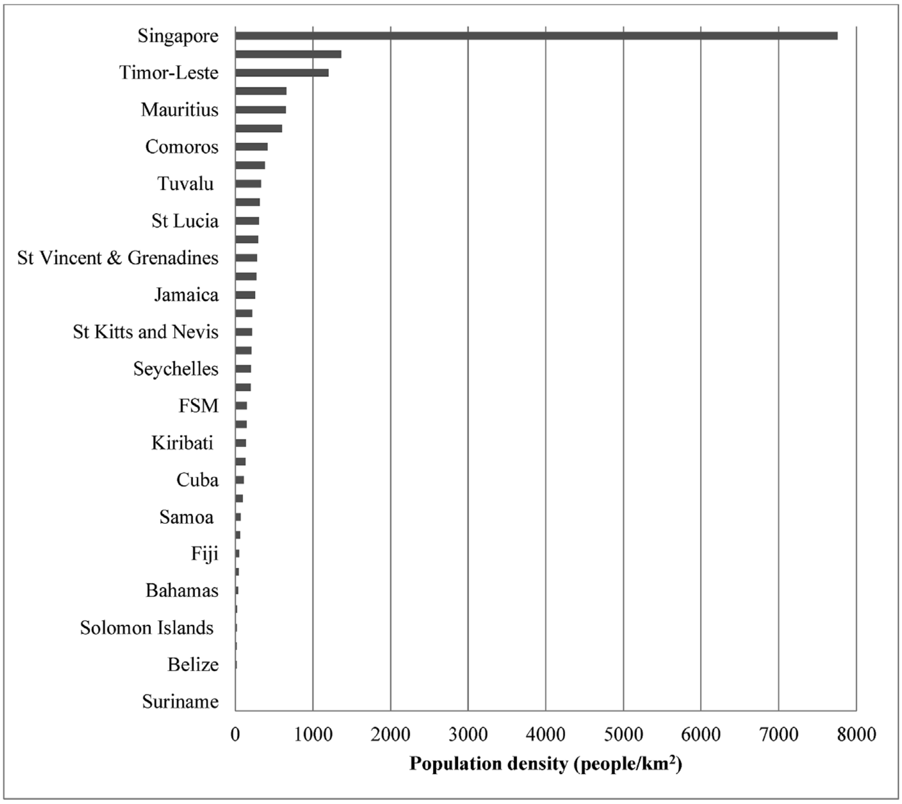

Fig. 1. Population density in SIDS (Authors' calculation based on World Bank, 2017a).

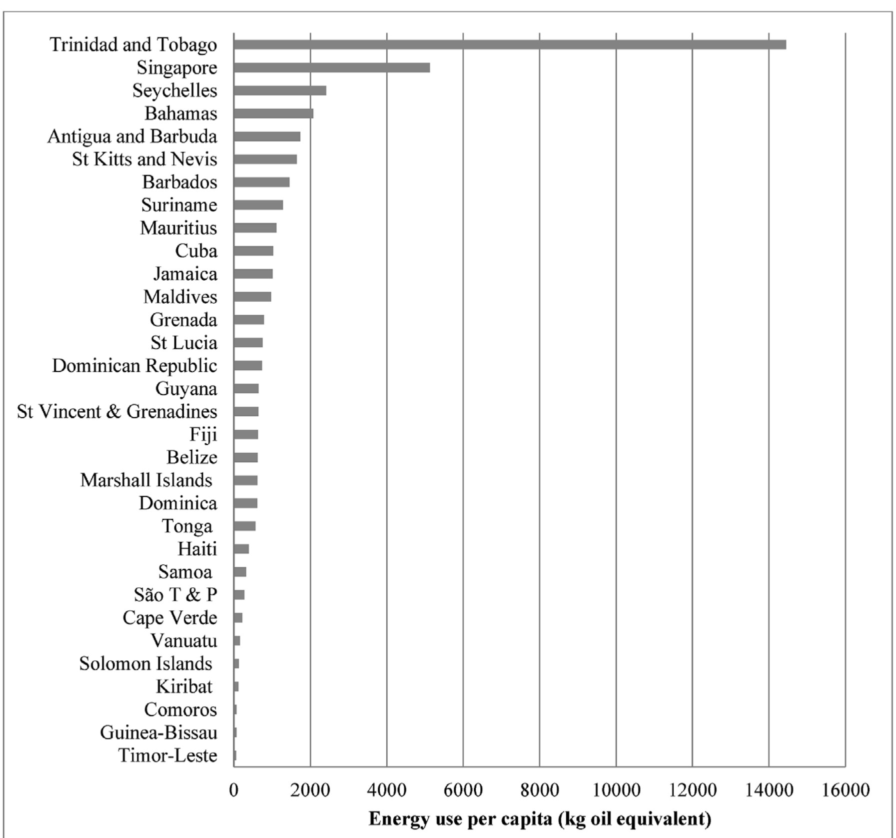

Fig. 2. Energy use per capita (Authors' calculation based on World Bank, 2017a).

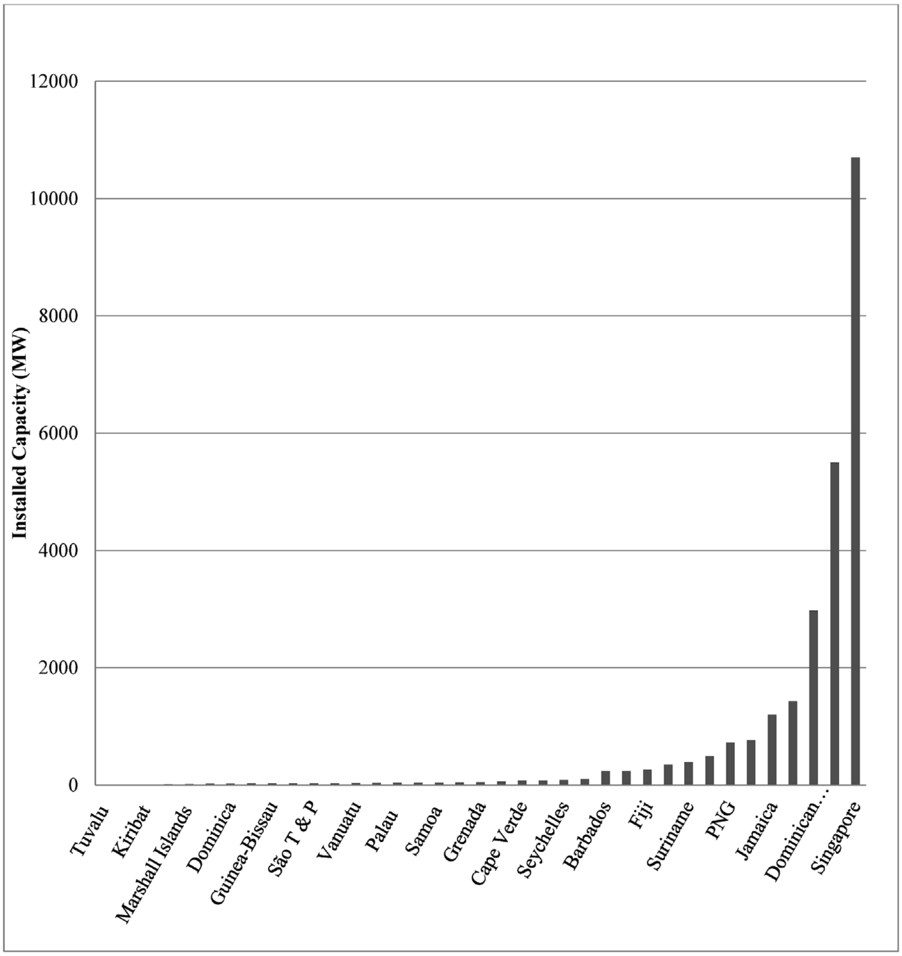

Fig. 3. Installed capacity (Source: IRENA, 2012, Shirley and Kammen, 2013; Prasad et al., 2017, Surroop and Raghoo, 2017).

impacts both natural and man-made systems in sometimes irascible 'domino effect', the strength of applying resilience systems theory to this global threat gained significant ground. Not the least because 'system dynamics' suggested a research pathway to revealing how to build capacity to deal with unexpected changes in eco- and socio-economic subsystems (Folke, 2006; Park et al., 2013).

When applied to the interface between the human and natural environments, a systems resilience approach takes as its unit of analysis, interactions between these sub-systems. The central questions under investigation become – how do these interactions survive, even thrive under threat of and actual abnormal or new disturbances. When the disturbance is climate change or more specifically climatic related impacts, then researchers are interested not only in the interactive elements but also how the resilience of these interactive elements, in turn, strengthen and build the sub-systems from which they emanate. Infrastructure as a subsystem of the human environment that is situated in the natural environment and impacted by climate change, is therefore an interesting area for application of resiliency theory. More intriguing becomes how the principles of how to make systems resilient can be applied to the study of islands as systems and threats to system viability such as environmental, economic or climatic change. Fig. 4 illustrates the principles of building resilient systems (developed by Biggs et al., 2012), with consideration of applicability to island systems.

If we were to take an analytical lens to contemporary studies of resiliency theory across a wide swarth of applied fields from electronics to pesticide chemistry to animal behavior, it will be found that resilient systems at most levels exhibit most of the seven characteristics in the diagram above, to varying degrees. As we investigate energy infrastructure on islands and their ability to withstand climatic impacts, it

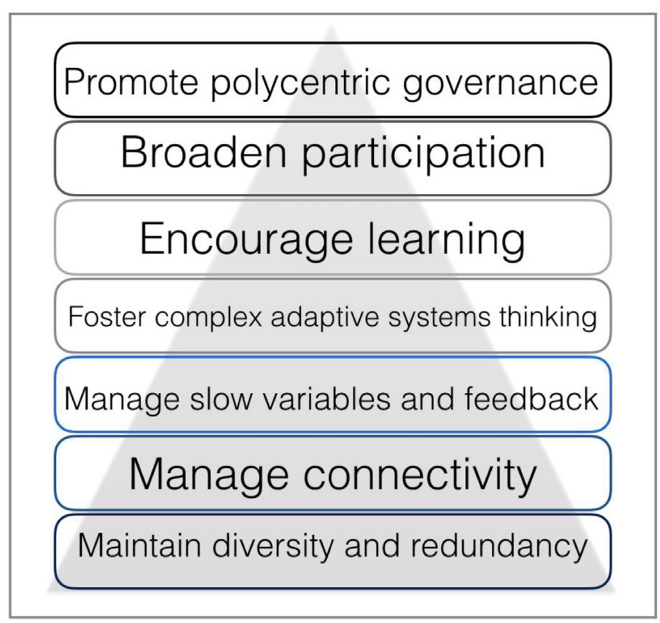

Fig. 4. Seven principles for improving the resilience of ecosystems (Authors' illustration based on the principles developed by Biggs et al., 2012).

becomes important to note if and how they exhibit these characteristics. The more often they do, the better. The seven principles developed by Biggs et al. (2012), when applied to SIDS, may be elaborated as follows:

(i) When a system comprises of multiple dimensions or components, if one or a few happen to fail, there is a greater likelihood that others can still function and take up the slack. Furthermore, should a system suffer a negative impact, where there are dimensions or components that are dissimilar from each other, they may be impacted differently, to different degrees or not at all. This *redundancy and diversity* of elements and components of a system, therefore build resiliency. The more that a system can maintain such characteristics, the greater the likelihood that it will weather potential impacts. In island systems with limited and finite options of geography, economy and resources, this becomes challenging without external interventions.

(ii) The numbers of linkages that components within a given system have as well as the linkages that the particular system has with other systems, is termed its connectivity. By and large, connectivity is a resiliency building characteristics in two ways. First, connectivity serves to spread risk across the system's parts. In so doing, the system as a whole is better able to absorb the shock of impacts and remain ‘online’ or functional. Second, the more interconnected the system is, the more ability it has to share resources in times of stress. This characteristics becomes most important when negative impacts drawn down on scare resources and the connectivity allows a system wide redistribution of those scare resources to where they are most needed. Similarly, connectivity provides a measure of control across the system and if one part sustains damage, it can essentially be ‘shut off’ to avoid contamination of other parts.

(iii) For the most part, we tend to visualize climatic impacts as extreme weather events that understandingly draw broad attention. But more and more, it is the slow onset impacts of climate change, that is, those that persist over time, that may be the most devastating and difficult to manage. Many resilient systems therefore exhibit mechanisms designed to stem these less observable, often insidious impacts and keep them in check. One way is via feedback connections that either positively reinforce a particular change to the system or negatively reinforce such changes. In a generalized example, a slow onset of a steady flow of resources could be positively absorbed and stored by the system for future usage, but after a tipping point, perhaps attaining supply storage capacity, a negative feedback kicks in to reduce the flow of the resource into the system in the future. Should this not occur, system integrity could be compromised.

(iv) While as previously stated, the connectivity characteristic is a resiliency builder, it is not just a matter of quantity of connections internal and external to the system but also the quality of connections. This points to the observations that the more unexpected the connections, the greater likelihood that some innovative, new and sometimes per chance way of building resilience to impacts, becomes apparent. ‘Run of the mill’, expected connectivity only goes so far for most systems and does little when the system is confronted by higher levels of unpredictability and uncertainty.

(v) Many highly resilient systems become so because they learn from past experiences and encourage further learning throughout the sub-systems of which they are comprised. To adapt, especially to new, abnormal or unforeseen impacts, systems have to encourage features that allow learning at multiple levels of operations. This learning must also be absorbed and recapitulated as action in the face of impending risks. Wherever socio-ecological systems an stimulate learning, there is greater likelihood of survival through adaptation and further resiliency building.

(vi) Systems that comprise of fully engaged, active and broad, well-functioning participation of its sub-components can benefit more so those systems that do comprise of multiple diverse components but many of innate or inactive or operating independently. In socio-economic systems for example, one advantage of broad, engaged participation is the opportunity to for individual groups, communities or constituencies to gain experience of interactions amongst others. This not only hones each group or sub-system's own operational effectiveness but also serves to build confidence in each other and mutual trust. Trust among diverse and distant groups that must work together for a common cause, especially in the face of unpredictable impacts, becomes an advantage to resiliency building.

(vii) How are decisions made in these complex multi-subsystem contexts? This question is often at the heart of how systems react to unpredictability and hence the quality and success of their adaptation processes. Conceivably, the potential exists for each of the numerous sub-systems or components to have its own decision making criteria and process and derive opposing action decisions to combat impeding impacts. The systems that survive and exhibit the most resilience are in fact those systems that do not necessarily suppress these subsystem tensions but align them into what is often termed polycentric governance. Here, there are multiple decision making or governing bodies that collaborate with each other according to their own spheres of influence to chart actions and also to devise rules of engagement for combating risk. Such systems have been deemed as more flexible and reflexive in their ability to modify systemic behaviors that mediate between the various subsystems to illicit collective outcomes. The flexibility here is often juxtaposed with more ridged, formalized decision making or governance systems which find it difficult to compromise, make trade-offs and cope with unforeseen disturbances.

4. Considering the impacts of climate change on energy infrastructure resilience

Extreme weather conditions such as cyclones/hurricanes, droughts and floods are some of the most discernible impacts of climate change with more severe and intense weather conditions now being observed. These extreme weather conditions may result in natural disasters in SIDS depending on the exposure and vulnerability of inhabited locations, infrastructures and agriculture (Banholzer et al., 2014; Helmer and Hilhorst, 2006; IPCC, 2012). The least exposed and more resilient are these settlements, the lower the risk of being impacted by an extreme weather condition. Among the several damages suffered by SIDS due to extreme weather conditions, the impacts on energy infrastructures are often among the most significant and these result mainly from the devastating winds and floods associated with these weather events. Extreme winds impact on energy infrastructures such as overhead power or transmission lines, distribution lines, utility poles, substations or wind turbines. High amount of rainfall due to cyclones, hurricanes or floods saturates the soil and renders trees more vulnerable to being uprooted with winds (Fitzpatrick, 2006) and these trees fall down, damaging electric transmission or distribution lines and utility poles. As for droughts, these do not impact the aforementioned energy infrastructures but for SIDS relying on renewable energy from hydropower or plant biomass, droughts may have a damaging impact on these two sources of energy. With low rainfall, hydropower plants do not operate at their installed capacities while plant biomasses are also affected, thereby increasing the risks of power outages. The impacts of extreme weather conditions on energy infrastructures in SIDS are further assessed by regions as follows.

4.1. AIMS SIDS

Among the nine AIMS SIDS, Mauritius is the most at risk to the impacts of extreme weather conditions as confirmed by its higher risk index in the WorldRiskIndex (United Nations University, 2016). The

higher risk index of Mauritius as opposed to the other AIMS SIDS is attributed to its higher exposure to tropical storms or cyclones (United Nations University, 2016), considering that the island is located on the path commonly taken by these tropical systems in the south-west Indian Ocean. Over the past 25 years until 2017, Mauritius has been impacted by 38 tropical systems with intensities varying from moderate tropical storms to intense tropical cyclones (Statistics Mauritius, 2016; Meteo France, 2017). During this period, the two most devastating systems were intense tropical cyclone Hollanda in 1994 with gusts reaching 216 km/h and very intense tropical cyclone Dina in 2002 with gusts recorded on the island reaching 228 km/h (Statistics Mauritius, 2016). Cyclone Hollanda directly impacted Mauritius and the energy infrastructure suffered devastating damages with electric poles uprooted, resulting in 60% of the island without electricity (Le Mauricien, 2015). Similarly, as a direct consequence of cyclone Dina in 2002, electrical transmission and distribution lines were severely impacted, with most of the island deprived of electricity (Panapress, 2002). The Central Electricity Board (CEB) which is the national electricity company could only provide 20% of electricity once the cyclonic conditions were over, with another 40% over the next few days and also reported that it would take one week for the whole island to be supplied back with electricity (Panapress, 2002; Pan African News Agency, 2002; UN Office for the Coordination of Humanitarian Affairs, 2002). In 1996, intense tropical cyclone Daniella passed at 40 km to the south west of Mauritius with gusts of 170 km/h being recorded, leaving 50% of CEB subscribers without electricity (Statistics Mauritius, 2016; Le Mauricien, 2015). In 2007, intense tropical cyclone Gamede passed at 230 km to the north west of Mauritius with gusts of 158 km/h being recorded on the island (Statistics Mauritius, 2016), affecting 60% of the electricity network due to significant damages caused to transformers and overhead power lines (L'Express, 2007).

Over the past 10 years up to 2017, 94 tropical systems (depressions, storms or cyclones) have developed in the south-west Indian Ocean, with an average of 4 of these tropical systems reaching the intensity of tropical cyclones or higher each cyclonic season (Meteo France, 2017). Out of these 94 systems, 9 have come close to Mauritius with maximum gusts reaching 104 km/h (Statistics Mauritius, 2016; Meteo France, 2017). Consequently, Mauritius has not suffered the damaging blows of storms or cyclones since 2008 and no major damage has been reported on energy infrastructures. Besides Mauritius, another AIMS SIDS that has been slightly concerned with cyclones is Comoros. Over the past 10 years up to 2017, only three tropical systems have approached the vicinity of Comoros: two as moderate tropical storms and one as a tropical cyclone (Meteo France, 2017). Only tropical system Hellen significantly affected Comoros as a moderate tropical storm in 2014, with power supply being affected in part of Moheli Island, which forms part of the Comoros (OCHA, 2014). In 2013, tropical depression Felleng impacted on another AIMS SIDS, Seychelles, mainly through downpour, damaging low-voltage electric poles and overhead lines mainly due to the falling down of trees although these did not significantly affect power supply (Government of Seychelles, 2013). Another AIMS SIDS recently and unexpectedly impacted by a hurricane is Cape Verde. This island, which is located to the west of Senegal in the Atlantic Ocean, is the place where hurricanes tend to form and then move in a westerly/north westerly direction away from the island. However, in 2015, hurricane Fred formed to the south east of Cape Verde, moved in a north-westerly direction and impacted on Cape Verde with intense flooding, severe damages to infrastructures and significant power loss (Ballou, 2015).

Besides cyclones, AIMS SIDS are also vulnerable to the impacts of floods and droughts. Floods may damage energy infrastructures such as substations and electrical equipment therein such as transformers and relays but these occur mainly as a result of cyclones with the impacts on AIMS SIDS mentioned previously. Nonetheless, as a result of climate change, a phenomenon that is becoming increasingly common is huge amount of rainfall in a small period of time, resulting in flash floods. In 2012, heavy rainfall in Comoros resulted in flash floods, impacting on power plants and affecting electricity supply (Union of Comoros and UNDP, 2012). In Maldives, flooding is caused mainly by tidal swells as a result of its low elevation above sea level and this impacted on electric poles and cables in 2015, causing power outages in two atolls (Hameed, 2015). As opposed to cyclones, hurricanes and floods, the impacts of droughts on energy infrastructures are less significant. Droughts may affect energy supply for economies highly dependent on hydroelectricity. For the AIMS SIDS, hydroelectric power contributes a very small share in electricity generation (São Tomé and Príncipe: 9.1%, Mauritius: 4.2%, Comoros: 3.7%, remaining AIMS SIDS: 0%) (EIA, 2018) and drought periods may not significantly impact on the electricity sector. Nonetheless, in 1999, a lack of rainfall resulted in Mauritius facing a severe drought spell (Mauritius Meteorological Services, 2017). In the same year, electricity production from hydropower plants dropped to 30.0 GWh, a decrease of 71.3% as opposed to hydroelectricity production in 1998 (Statistics Mauritius, 2015). Similarly, in 2011, Mauritius suffered from another drought period, with its largest reservoir emptied to almost 75% (Business Mega, 2011). In the same year, hydroelectricity production dropped to 56.5 GWh, representing a decrease of 43.9% as opposed to the previous year (Statistics Mauritius, 2015). For the other AIMS SIDS, no significant impacts of droughts on hydroelectricity production have been reported.

4.2. Caribbean SIDS

Hurricanes in the North Atlantic Ocean tend to have a westerly or north-westerly movement with some of them then following a curving trajectory to a north and north-easterly direction. Based on the locations where hurricanes tend to form in the North Atlantic Ocean, their most common trajectories and the locations of the Caribbean SIDS, these small islands are particularly exposed to the damaging impacts of these extreme weather conditions. From 2007 to 2016, 157 tropical systems were formed in the North Atlantic Ocean with 65 reaching intensities of hurricanes (NHC, 2017). One of the strongest hurricanes in the Atlantic Ocean was hurricane Wilma in 2005 (Williams, 2015), impacting on several SIDS namely Cuba, the Bahamas, Haiti and Jamaica with sustained winds of 193 km/h recorded in Bahamas, damaging utility poles (International Federation of Red Cross and Red Crescent Societies, 2006). In 2007, hurricane Dean with offshore winds of 240 km/h battered Jamaica, impacting significantly on electricity infrastructures such as electric poles (Carroll, 2007; Elsworth et al., 2007). In the same year, hurricane Felix with sustained winds of 129 km/h damaged electric poles in Grenada (Los Angeles Times, 2007). In 2008, Cuba felt the wrath of hurricanes Gustav, Ike and Paloma, significantly impacting on electricity cables, electric poles and affecting the electricity network (UN Office for the Coordination of Humanitarian Affairs, 2008; ACT, 2008; Daily Mail, 2008). In the same year, hurricane Omar passed near the Netherlands Antilles, damaging power lines and depriving the population of electricity (International Federation of Red Cross and Red Crescent Societies, 2008). In 2010, hurricane Earl swept over Antigua and Barbuda, Anguilla and the British Virgin Islands with severe damages to infrastructures and utility poles, depriving thousands of people of electricity (CBS News, 2010). In the same year, hurricane Tomas caused serious damages on power lines in Barbados, St. Vincent and the Grenadines and St. Lucia, resulting in power outages in these islands (Pasch and Kimberlain, 2011). In 2011, hurricane Irene battered Puerto Rico, leaving over a million people without electricity (CBS News, 2011) before hammering the Bahamas, destroying power lines and utility poles, with several localities without electricity (Caribbean Disaster Emergency Management Agency, 2011). In 2012, hurricane Sandy impacted Jamaica and damaged utility lines prior to making landfall on Cuba, impacting severely on electrical networks, with 50% of the residents in some localities reported to be without electricity (Associated Press, 2012; Cuba Hurricanes, 2012). In 2014, hurricane Gonzalo passed over Anguilla and Antigua and

Barbuda, damaging power lines and causing power outages (Brown, 2015). In 2015, hurricane Joaquin passed near the Bahamas with gusts of 225 km/h, impacting on energy infrastructures and causing power outages in several islands (Curaçao Cronicle, 2015). In 2016, hurricane Matthew made landfall on Haiti, Cuba and the Bahamas with gusts of 244 km/h and 206 km/h recorded in Cuba and the Bahamas respectively and severely damaged utility lines and electric poles, with 80% of residents in some localities deprived of electricity (Stewart, 2017). In 2017, the Caribbean SIDS were impacted by two extremely devastating hurricanes namely Irma and Maria and to a lesser extent by Hurricane Jose. Hurricane Irma severely damaged infrastructures in Barbuda, British Virgin Islands, US Virgin Islands, Puerto Rico and Cuba (Belluz, 2017). In many of these SIDS, energy infrastructures including electric lines and poles suffered the full blows of hurricane Irma, leaving many of these islands without electricity (Financial Times, 2017; Faiola, 2017). In Puerto Rico, one million people were deprived of electricity following hurricane Irma (Resnick and Barclay, 2017). In the same year, hurricane Jose passed in the vicinity of Anguilla with a few electric transmissions lines damaged (Caribbean Disaster Emergency Response Agency, 2017). Later in 2017, hurricane Maria made landfall on Puerto Rico with winds up to 249 km/h, damaging 80% of electrical transmission lines, leaving more than 1.35 million of customers without electricity (Resnick and Barclay, 2017; The Telegraph, 2017). Prior to Puerto Rico, hurricane Maria damaged electrical infrastructures in Dominica and US Virgin Islands, leaving 73% of residents in the US Virgin Islands deprived of electricity even 2 months after the hurricane (Phipps, 2017; Raphelson, 2017). As aforementioned, droughts are not particularly devastating on energy infrastructures except for those islands heavily dependent on hydroelectricity. Unlike AIMS SIDS, hydropower is a major source of electricity generation in some Caribbean SIDS such as Belize (63.7%), Suriname (53.8%), Haiti (28.7%), Dominica (24.5%) and St. Vincent and the Grenadines (16.1%) (EIA, 2018) and any drought periods may significantly impact on electricity generation in these islands. In 2009–2010, the Caribbean SIDS experienced one of their worst droughts with hydroelectricity production particularly impacted in St. Vincent and the Grenadines (FAO, 2016). However, with the frequency and severity of droughts expected to increase in the future (FAO, 2016), this will unfortunately impact on hydroelectricity production in these Caribbean SIDS.

4.3. Pacific SIDS

Cyclones in the South Pacific Ocean follow varying trajectories with some possessing an initial westerly/south-westerly movement followed by a southerly/south-easterly movement while others have a south-easterly movement only. Over the past years, a considerable number of tropical systems have developed in the South Pacific Ocean, with some of them reaching intensities never experienced before. In 2003, severe tropical cyclone Erica hit New Caledonia with damaging impacts on the energy infrastructure and 80% of the north of the island deprived of electricity (East-West Center, 2003). In 2004, severe tropical cyclone Heta impacted on American Samoa, Samoa and Niue with power lines severely impacted (Australian Agency for International Development, 2004; Deutsche Presse Agentur, 2004). In the same year, cyclone Ivy impacted on Vanuatu, interrupting electricity supply in several areas (Government of New Zealand, 2004). In 2005, cyclone Nancy with gusts up to 185 km/h impacted on southern Cook Islands with power stations, poles and lines damaged by the strong winds (Padgett, 2005). In the same year, cyclone Olaf again affected Cook Islands, with 30–40% of households in Rarotonga deprived of electricity due to significant damage to power lines (Padgett, 2005). In 2010, tropical cyclone Rene impacted on Tonga with winds over 160 km/h, again damaging electricity supply (World Health Organisation, 2010). In the same year, tropical cyclone Pat impacted on Cook Islands with gusts reaching 185 km/h, causing damages to several infrastructures including the electricity network (UN Office for the Coordination of Humanitarian Affairs, 2010). In 2011, cyclone Wilma impacted on American Samoa damaging power lines and depriving many villages of electricity (ABS Radio Australia, 2012). Later, severe tropical cyclone Wilma impacted on the electrical network in Tonga (Ministry of Information & Communications, 2011). In 2012, cyclone Evan, with winds reaching 185 km/h, damaged the main power plant in Samoa, resulting in power outages for more than 10 days (Masters, 2012). In the same year, cyclone Jasmine flooded Tonga with electricity lines damaged, causing temporary power outages (Field, 2012). In 2014, cyclone Ian impacted on 90% of network lines, 65% of transformers and a generator, leaving 971 customers deprived of electricity in Tonga (PIDP, 2016). In 2015, severe tropical cyclone Pam battered several Pacific SIDS with the impacts significantly felt on Vanuatu with gusts reaching 340 km/h (Fox, 2015), damaging electric posts and lines and affecting low and high voltage networks, resulting in blackouts (Ligo, 2016). In 2016, tropical cyclone Ula damaged power lines causing part of Tonga deprived of electricity (Stuff, 2016). In the same year, severe tropical cyclone Winston, with 1-min sustained winds of 290 km/h, made landfall on Fiji, damaged power lines and deprived 80% of Fijians of electricity (Uhlhorn, 2016), with some affected areas without electricity for a month (UNICEF, 2016). In 2017, cyclone Cook with gusts reaching 130 km/h impacted on Vanuatu, causing several parts of Port Vila deprived of electricity (MacGregor, 2017). The same cyclone then impacted New Caledonia with gusts reaching 180 km/h, leaving approximately 70,000 people without electricity (Packham and Greenfield, 2017). Similar to AIMS and Caribbean SIDS, Pacific SIDS are also vulnerable to drought periods and this eventually impacts on hydroelectricity production. Hydropower is not a major source of electricity generation in most Pacific SIDS except for Fiji (45.5%), Samoa (31.5%) and PNG (27.0%) (EIA, 2018). As such, any drought periods may significantly impact on electricity production and supply in these small islands.

5. Discussion: resiliency of energy infrastructure systems in SIDS

Resilience can formally be defined as *"the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks"* (Walker et al., 2004). Resilience theory and its application to energy infrastructure systems views climate proofing as the continuous adaptive measures taken, that are driven by chronic extreme weather disturbances. While resilience theory was first developed by ecologists to explain how natural ecosystems adapt to external stressors, it can similarly provide a framework for policy makers to think about how island energy infrastructure systems can be adapted to respond to increasing climate-induced extreme weather events.

According to the resilience theory, a system is able to maintain functioning and expand by favoring components with high adaptability in response to external stressors (Gunderson and Holling, 2002; Allen et al., 2014; Clément and Rivera, 2017). The resilience of any energy infrastructure is dependent on three component factors namely robustness, resourcefulness and recovery of the system (OECD/IEA, 2015). For energy infrastructure to be robust, for example, utility lines and poles must be able to withstand extreme wind conditions while other electrical equipment such as transformers must remain operational so as to ensure that electricity is continuously supplied to the subscribers (OECD/IEA, 2015). Electricity is often interrupted during cyclones or hurricanes with electricity lines and electric poles severely damaged, implying lack of robustness. The resourcefulness of an energy system is the ability to gather resources to overcome any impacts caused to an energy infrastructure so as to ensure that operations are efficiently managed (Power Grid Corporation of India Ltd, 2015; OECD/IEA, 2015). For instance, resources must be put in place to ensure that electricity is supplied as long as possible while emergency centres viz. hospitals must be continuously supplied with electricity. Following the aftermath of an extreme weather event, the recovery of

an energy infrastructure is the capacity to re-establish electrical connections to the subscribers (OECD/IEA, 2015). Recovery time can vary from a few days to months depending on the damages caused to the electrical infrastructures.

Energy infrastructure systems in SIDS are lacking to varying degrees in each of the three components – robustness, resourcefulness and recovery. To make more robust, countries take numerous measures, with different degrees of success. In Seychelles, for example, trees that may represent a danger to electrical transmission lines are cleared (Government of Seychelles, 2013). In Mauritius, power plants and other substations are located in areas less prone to contact with water while these energy infrastructures also cater for drainage during cyclones or flash floods (Mukoon, 2013). In addition, power plants, transmission lines, towers and switchgears in Mauritius are designed to withstand the impacts of cyclones while some transmission lines are installed underground although these are often more costly (Mukoon, 2013). Power outages during extreme weather conditions often occur as a result of damages to one of the connections (power lines, electric poles, transformers) in the centralised grid system. With off the grid electrification systems or small-scale decentralised grid systems such as small-scale solar energy or wind turbines, potential power outages or blackouts during extreme weather events are reduced even if the centralised grid system is affected.

A similar approach is being envisaged in the Caribbean SIDS following Hurricane Irma with decentralised renewable energy systems being at the forefront of the development of a more resilient Caribbean region (Burgess et al., 2017). In October 2017, the Caribbean Renewable Energy Forum (CREF), launched in 2009, focussed its discussions on building a more resilient energy system in the Caribbean region following hurricanes Irma and Maria (Caribbean News Now, 2017). In Puerto Rico, the devastating impacts of Hurricane Maria on the energy infrastructure have triggered a shift towards off-grid renewable energy, particularly solar energy (Irfan, 2017; Bryant, 2017). In Haiti, two grants amounting to USD 35 million have been approved by the World Bank to increase the resilience of the energy infrastructure and provide Haitians with sustainable and clean energy focussing on off-grid electrification including hydropower, wind energy and bio-energy (Shah et al., 2014; World Bank, 2017b).

The situation is not dissimilar in Pacific SIDS. Fiji, for instance, is targeting 100% renewable electricity generation by 2036 in its National Development Plan, with many decentralised energy systems (solar, hydropower) planned while underground cables are also envisaged (where viable) so as to have a more resilient energy infrastructure (Ministry of Economy, 2017). Likewise, Samoa is targeting 100% renewable electricity generation by 2025 and recently launched the "IMPRESS" project, focussing on renewable energy exploitation (UNDP, 2017).

Even as these 'climate proofing' efforts are made however, we must remain cognizant that resilience theory warns that as energy infrastructure system functions and processes become more established and interconnected, the system itself may eventually become less flexible, which may weaken its capacity to counter further external disturbances (Holling, 2001; Gunderson and Holling, 2002; Allen et al., 2014; Clément and Rivera, 2017). This presents a long term quandary for policy makers especially if climatic change impacts are forecast to increase and/or become more erratic.

6. Framing climate resilience based policy for energy infrastructure systems

In our proposed approach, government policy makers view energy infrastructure systems as open adaptive systems with varying capacities to absorb and/or respond to external disturbances. Climate proofing policies focus on incentivizing energy infrastructure systems to progress through robustness, resourcefulness and recovery as they attempt to cope with climatic changes as well as economic conditions that induce expansion, diversification and technical sophistication.

Fig. 5 shows the graph of installed capacity against the world risk index. It is noted that Vanuatu and Tonga are the most vulnerable SIDS and this has been demonstrated by the damages after cyclone Pam in Vanuatu and recent cyclone Gita in Tonga. It should be noted that some SIDS (Antigua and Barbuda, Dominica, Federated States of Micronesia, Maldives, Marshall Islands, Nauru, Palau, Saint Lucia, Samoa, São Tomé and Príncipe, St. Kitts and Nevis, St. Vincent and Grenadines) are not included in the list of world risk index due to lack of data.

Based on the available country data graphed here, an interesting picture of SIDS energy infrastructure systems and weather risk emerges. There are several countries that could be considered as outliers, for example the Dominican Republic with significantly higher installed capacity or Vanuatu with its significantly higher weather risk index than the majority of other SIDS.[1] When viewing this data, it should not be ignored however, that all of the SIDS typically carry higher weather risk indices and installed capacities on the lower end of the scale relative to most other countries.

The spectrum of SIDS by energy infrastructure system capacity and weather risk index can be considered of being comprised of four contiguous 'clusters' that correspond relatively to the conceptualization in resilience theory, of systems at different stages of adaptive cycles. Applied to this case, we find that cluster 1, comprising of countries such as the Dominican Republic, Cuba and Trinidad & Tobago are characterized by high installed capacity, relatively robust, resourceful and high recovery infrastructure systems and processes coupled with relatively lower weather risk compared to other SIDS. Cluster 2, comprising of countries such as PNG, Mauritius and Jamaica are also characterized by relatively high installed capacity and infrastructure systems that are reasonably robust, resourceful and high recovery. The majority of SIDS appears to fall into either cluster 3 or cluster 4. Cluster 3, comprising of countries that include Cape Verde, Haiti, Timor-Leste and Fiji are characterized by lower installed capacities with infrastructure systems that are relatively less robust, less resourceful and less recovery ready than those of cluster 1 or cluster 2. But like cluster 2, countries in cluster 3 are also more at risk of extreme weather events. Lastly, cluster 4 countries such as Kiribati, Seychelles and Barbados have both relatively low installed capacities and weaker energy infrastructure robustness, resourcefulness and recovery readiness as but relatively lower weather risk index than SIDS in cluster 2 and cluster 3.

SIDS clearly have to consider where they fall within this cluster scenario, in order to frame more relevant and effective policy strategies. Researchers cite a variety of dimensions to be addressed to build and tailor energy infrastructure resilience at the specific country level. There are however two fundamental ways for SIDS policy makers to start thinking about how to frame a national policy approach. The first dimension is the energy value chain from securing fuels to generation, transmission, distribution and consumption. Within each of these value chain stages, policy makers then have to consider three factors – stability, viability and integrity (Schaeffer et al., 2012). This cross-matrix policy formulation approach allows SIDS to consider both fossil fuel usage as well as renewable sources of energy in the value chain. It also allows policy makers to embed a certain level of flexibility in policy design to account for issues such as grid expansion to cater for economic development and increased electrification (Shah and Rivera, 2007).

Based on this cross-matrix approach, there are six general policy framework dimensions that become indispensable in building energy infrastructure system resilience as follows:

I. *Policy approach to centralization/decentralization systems:* Most developments continue to bend towards centralised power systems

[1] Cuba is omitted from the graph as a matter of illustrative convenience, given its high installed capacity.

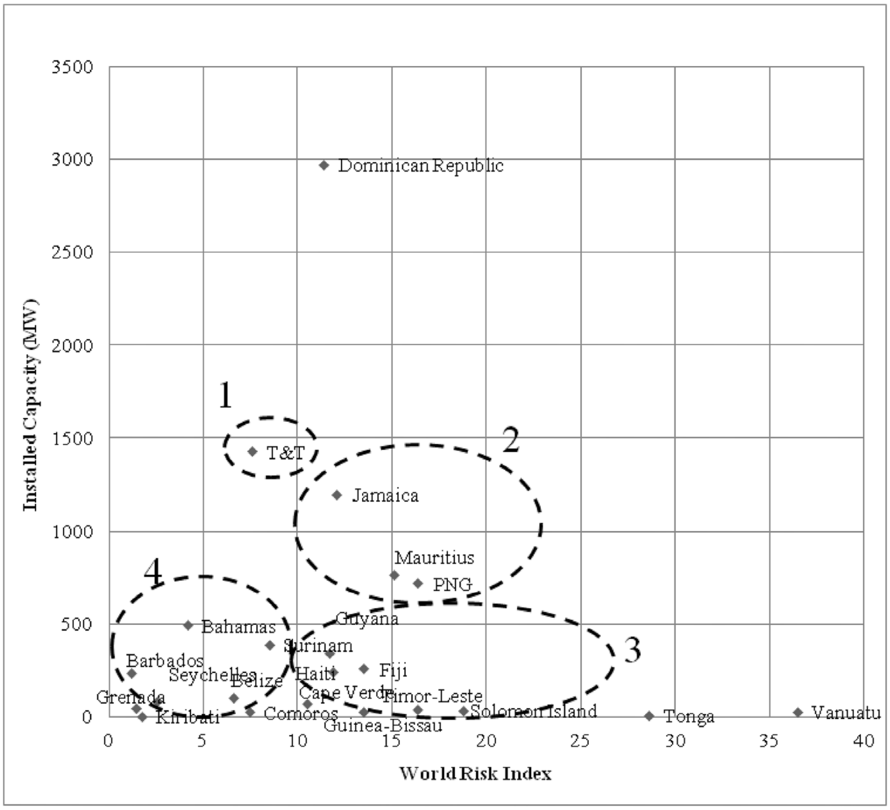

Fig. 5. Installed capacity (MW) vs. world risk index for available SIDS Source: IRENA, 2012, Shirley and Kammen, 2013, Prasad et al., 2017, Surroop and Raghoo, 2017, World Risk Report, 2017).

but the materialization of regional efforts could provide enhanced system efficiencies with better service (Amin, 2004). Extreme weather events expose the vulnerabilities of centralised control systems. Climate proofing on islands may demand smaller, local systems as the systemic configuration.

II. *Policy approaches that recognize escalating difficulties:* Modernizing systems through integration with the intentions of increased efficiency and spread of electrification in extreme weather events and the aftermath can also potentially make the systems more complicated and tougher to control and manage (Amin, 2004). This must therefore be carefully considered alongside government resources, expertise and budgeting to handle such operations.

III. *Policy on maintaining communications across island energy systems:* Effective energy infrastructure operations are held together, more and more, by the strength of their communication capacity (Amin, 2004). With increasing support and reliance on internet and wireless-based communications technologies, this aspect becomes crucial to maintain in the event of extreme weather conditions and their aftermath.

IV. *Policy approaches that address climate proofing priorities:* Energy infrastructure system components may be remotely located from one another. Hence, policy makers have to be ready to set criteria across the board whereby these infrastructure system components are priority for climate proofing and allocate relevant, admittedly scarce resources to do so. This implies, among others, the deployment of appropriate techniques for siting of the energy infrastructure system components based on observed and anticipated climate change-induced impacts and their locations.

V. *Policy approaches that incentivize or allocate resources toward infrastructure survival:* As island energy infrastructure expands, including through private investorships, standards that promote resilient design, construction, operation and retrofitting become indispensable. These regulatory specifications should be directed towards critical infrastructure system components with highest vulnerabilities (e.g. maritime transfer stations and ports).

VI. *Policy approaches that support infrastructure recovery:* The objective here is to mitigate the impacts of extreme weather impacts. Government agencies, often specialized for this task can be empowered to provide a range of emergency aid programs including reparation of public utilities in affected areas.

VII. *Policy approaches that seek to prioritize human survival and recovery*: In the face of climate induced extreme weather events, energy infrastructure should focus on the most vulnerable groups and communities especially in terms of energy access and reliability. In SIDS this can also mean communities at higher risk because of geographic remoteness and lack of transportation.

Lastly, circling back to the fundamentals of resilience theory and its application to energy infrastructure systems, it is important to remember that resiliency building is a cyclic, continuous improvement undertaking (the adaptive cycle). As such, the best policies will be set up to understand and even leverage that anticipation. Resilient infrastructure is built pre-weather event in anticipation and also in post-event aftermath, having learned from the lessons of damage and devastation that may have occurred. In cycles therefore, the six policy approaches outlined above, should in an integrative manner, lend to the climate proofing process over time.

7. Conclusion

Extreme weather conditions such as cyclones, hurricanes and floods are having damaging impacts around the world with settlements, infrastructures, agriculture and economies severely affected. As reviewed in this article, SIDS are particularly exposed and vulnerable to extreme weather conditions and the impacts on the energy infrastructures in these small developing economies are often devastating. The lack of

robustness of the energy infrastructures in SIDS and the long recovery time following damage are two factors responsible for the low resilience of the energy infrastructures in these small developing economies. In the same line, policy intervention is another area that requires further research to investigate its impacts on the resilience of energy systems in SIDS.

Resiliency is a continuous process and resilient infrastructures are built either in anticipation of a damage or from lessons learned following a damage. As such, this article proposed a policy level framework, based on the resilience theory, to increase the resilience of the energy systems in SIDS. The policy framework is based on decentralised energy systems which are less complex and more interactive between SIDS. The framework also proposes approaches that assist in the quick recovery of energy infrastructures following damages from extreme weather conditions. The different approaches proposed in the policy framework, when integrated, will assist in building the resilience of energy infrastructures in SIDS over time.

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References

Ministry of Information & Communications, 2011. Cabinet Established Cyclone Wilma Relief Fund with TOP 1 Million. http://www.mic.gov.to/government/state-of-emergency/2118-cabinet-establishes-cyclone-wilma-relief-fund-with-top-1-million, Accessed date: 17 December 2017.

ABC Radio Australia, 2012. Cyclone Wilma Causes Damage in American Samoa. http://www.radioaustralia.net.au/international/radio/onairhighlights/cyclone-wilma-causes-damage-in-american-samoa, Accessed date: 17 December 2017.

ACT, 2008. ACT Alert Cuba No. 37/2008: Hurricane Ike. Action by Churches Together International. https://reliefweb.int/report/cuba/act-alert-cuba-no-372008-hurricane-ike, Accessed date: 21 December 2017.

Allen, C.R., Angeler, D.G., Garmestani, A.S., Gunderson, L.H., Holling, C.S., 2014. Panarchy: theory and application. Ecosystems 17, 578–589. https://doi.org/10.1007/s10021-013-9744-2.

Amin, M., 2004. Balancing market priorities with security issues. IEEE Power Energy Mag. 30–38.

Associated Press, 2012. Hurricane Sandy Pounds Jamaica, Then Aims at Cuba. http://newsinfo.inquirer.net/295494/hurricane-sandy-pounds-jamaica-then-aims-at-cuba, Accessed date: 22 December 2017.

Australian Agency for International Development, 2004. Cyclone Heta Updated 9 Jan 2004. https://reliefweb.int/report/niue-new-zealand/cyclone-heta-updated-9-jan-2004, Accessed date: 15 December 2017.

Ballou, B., 2015. Local Cape Verde Natives Fear for Storm-wracked Homeland. http://www.sun-sentinel.com/local/broward/fl-fred-local-impact-20150831-story.html, Accessed date: 11 December 2017.

Banholzer, S., Kossin, J., Donner, S., 2014. The impact of climate change on natural disasters. In: Zommers, Z., Singh, A. (Eds.), Reducing Disaster: Early Warning Systems 21 for Climate Change. Springer Science + Business Media, Dordrecht, pp. 21–49. https://doi.org/10.1007/978-94-017-8598-3_2.

Belluz, J., 2017. It's Not Just Puerto Rico: 6 Other Caribbean Island Nations Are in Crisis after the Hurricanes. https://www.vox.com/science-and-health/2017/9/26/16367410/hurricane-maria-2017-puerto-rico-caribbean-barbuda-dominica-virgin-islands-cuba-st-martin, Accessed date: 28 December 2017.

Biggs, R., Schlüter, M., Biggs, D., et al., 2012. Towards principles for enhancing the resilience of ecosystem services. Annu. Rev. Environ. Resour. 37, 421–448.

Brown, D.P., 2015. National Hurricane Center Tropical Cyclone Report: Hurricane Gonzalo (AL082014). NOAA and National Weather Services.

Bryant, E., 2017. Remake Puerto Rico's Power Grid and Create a Universal Basic Income. http://www.climatechangenews.com/2017/12/06/rebuild-puerto-ricos-power-grid-create-universal-basic-income/, Accessed date: 7 January 2018.

Burgess, C., Locke, J., Doig, S., 2017. Rebuilding the Caribbean for a Resilient and Renewable Future. https://www.rmi.org/news/rebuilding-caribbean-resilient-renewable-future/, Accessed date: 6 October 2017.

Business Mega, 2011. Mauritius_Water: the Country Will Be Dry in 75 Days. https://business.mega.mu/2011/12/12/water-country-will-be-dry-75-days/, Accessed date: 12 December 2017.

Caribbean Disaster Emergency Management Agency, 2011. Situation Report #4 Hurricane Irene Impact on Turks and Caicos Islands and the Bahamas. (as at 5:00 p.m.). https://reliefweb.int/report/bahamas/situation-report-4-hurricane-irene-impact-turks-and-caicos-islands-and-bahamas-500-pm, Accessed date: 22 December 2017.

Caribbean Disaster Emergency Response Agency, 2017. Hurricane Jose Post Impact Situation Report #2. . https://reliefweb.int/report/anguilla/hurricane-jose-post-impact-situation-report-2, Accessed date: 28 December 2017.

Caribbean News Now, 2017. Calls for Renewable Energy Rebuild in the Caribbean. http://wp.caribbeannewsnow.com/2017/10/19/calls-renewable-energy-rebuild-caribbean/, Accessed date: 7 January 2018.

Carroll, R., 2007. Thousands Seek Shelter as Hurricane Dean Hits Jamaica. https://www.theguardian.com/world/2007/aug/20/naturaldisasters.rorycarroll, Accessed date: 20 December 2017.

CBS News, 2010. Hurricane Earl Batters Caribbean Islands. https://www.cbsnews.com/news/hurricane-earl-batters-caribbean-islands/, Accessed date: 22 December 2017.

CBS News, 2011. Hurricane Irene Slams Puerto Rico, Eyes U.S. https://www.cbsnews.com/news/hurricane-irene-slams-puerto-rico-eyes-us/, Accessed date: 22 December 2017.

Clément, V., Rivera, J., 2017. From adaptation to transformation: an extended research agenda for organizational resiliency to adversity in the natural environment. Organ. Environ. 30 (4), 346–365. https://doi.org/10.1177/1086026616658333.

Cuba Hurricanes, 2012. Hurricane Sandy. http://www.cubahurricanes.org/history-hurricane-sandy.php, Accessed date: 20 December 2017.

Curaçao Cronicle, 2015. Hurricane Joaquin Leaves Path of Destruction in Bahamas. http://curacaochronicle.com/region/hurricane-joaquin-leaves-path-of-destruction-in-bahamas/, Accessed date: 28 December 2017.

Daily Mail, 2008. Hurricane Paloma Hits Cuba as Hundreds of Thousands Are Evacuated. http://www.dailymail.co.uk/news/article-1084075/Hurricane-Paloma-hits-Cuba-hundreds-thousands-evacuated.html, Accessed date: 21 December 2017.

Deutsche Presse Agentur, 2004. Cyclone Heta Hits Tiny Pacific Island of Niue. https://reliefweb.int/report/niue-new-zealand/cyclone-heta-hits-tiny-pacific-island-niue, Accessed date: 15 December 2017.

East-West Center, 2003. Thousands Homeless after New Caledonia Cyclone. https://reliefweb.int/report/new-caledonia-france/thousands-homeless-after-new-caledonia-cyclone, Accessed date: 17 December 2017.

EIA, 2018. International Energy Statistics: Electricity Generation. U.S. Energy Information Administration. https://www.eia.gov, Accessed date: 13 February 2018.

Elsworth, C., Sheil, R., Beckford, M., 2007. Hurricane Dean Wrecks Havoc in Jamaica. Available from: http://www.telegraph.co.uk/news/worldnews/1560814/Hurricane-Dean-wreaks-havoc-in-Jamaica.html, Accessed date: 20 December 2017.

Faiola, A., 2017. There Is No Electricity, and Won't Be for Months. 'So what?' U.S. Virgin Islands Residents Say. https://www.washingtonpost.com/world/the_americas/there-is-no-electricity-and-wont-be-for-months-so-what-us-virgin-islands-residents-say/2017/09/13/cb2eb8b6-9888-11e7-af6a-6555caaeb8dc_story.html?utm_term=.c8c777286d73, Accessed date: 28 December 2017.

FAO, 2016. Drought Characteristics and Management in the Caribbean. FAO Water Reports 42. Caribbean Institute for Meteorology and Hydrology and Land and Water Division, FAO.

Field, M., 2012. Cyclone Jasmine Flooding in Tonga. http://www.stuff.co.nz/world/south-pacific/6422770/Cyclone-Jasmine-flooding-Tonga, Accessed date: 17 December 2017.

Financial Times, 2017. British Virgin Islands Financial Centre Hit Hard by Irma. https://www.ft.com/content/35183356-9609-11e7-b83c-9588e51488a0, Accessed date: 28 December 2017.

Fitzpatrick, P.J., 2006. Hurricanes: a Reference Handbook, second ed. Contemporary World Issues, ABC-CLIO Inc., USA, pp. 36.

Folke, C., 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. Global Environ. Change 16 (3), 253–267.

Fox, L., 2015. Tropical Cyclone Pam: Vanuatu Devastated by One of the Strongest Tropical Cyclones in Pacific; at Least Eight Dead. http://www.abc.net.au/news/2015-03-14/tc-pam-leaves-trail-of-destruction-as-it-moves-south-of-vanuatu/6318652, Accessed date: 17 December 2016.

Government of New Zealand, 2004. Cyclone Ivy: Status Report as at 4.30 Pm Fri 27 Feb 2004. . https://reliefweb.int/report/vanuatu/cyclone-ivy-status-report-430pm-fri-27-feb-2004, Accessed date: 17 December 2017.

Government of Seychelles, 2013. Seychelles Damage, Loss, and Needs Assessment (DaLA): 2013 Floods.

Gunderson, L.H., Holling, C.S., 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, DC.

Hameed, S., 2015. Two Northern Islands Hit by Tidal Swells. http://maldivesindependent.com/environment/two-northern-islands-hit-by-tidal-swells-121016, Accessed date: 12 December 2017.

Helmer, M., Hilhorst, D., 2006. Natural disasters and climate change. Disasters 30, 1–4. https://doi.org/10.1111/j.1467-9523.2006.00302.x.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

International Federation of Red Cross and Red Crescent Societies, 2006. Caribbean: Hurricane Wilma Emergency Appeal No. 05EA024. https://reliefweb.int/report/bahamas/caribbean-hurricane-wilma-emergency-appeal-no-05ea024, Accessed date: 20 December 2017.

International Federation of Red Cross and Red Crescent Societies, 2008. Caribbean: Hurricane Omar. Information Bulletin No. 1.

IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. IPCChttps://doi.org/10.1596/978-0-8213-8845-7.

IRENA, 2012. Renewable Energy Country Profiles. Special Edition on the Occasion of the Renewables and Islands Global Summit.

Irfan, U., 2017. Puerto Rico Is Starting to Take Solar Power More Seriously. https://www.vox.com/energy-and-environment/2017/10/19/16431312/elon-musk-richard-branson-clean-energy-puerto-rico-solar-batteries-microgrid, Accessed date: 7 January 2018.

Kennedy, C., Corfee-Morlot, J., 2013. Past performance and future needs for low carbon climate resilient infrastructure–An investment perspective. Energy Pol. 59, 773–783.

L'Express, 2007. Le CEB a-t-il disjoncté lors du cyclone Gamede? https://www.lexpress.

mu/article/le-ceb-t-il-disjonct%C3%A9-lors-du-cyclone-gamede, Accessed date: 11 December 2017.
Le Mauricien, 2015. Rappel: Cyclones, en un clin d'oeil. http://www.lemauricien.com/article/rappel-cyclones-en-clin-d-oeil, Accessed date: 11 December 2017.
Ligo, G., 2016. Restoring Water and Electricity after Cyclone Pam. http://dailypost.vu/news/restoring-water-and-electricity-after-cyclone-pam/article_55ed1b5b-ee9a-580d-9c92-5bbb94a7f6ab.html, Accessed date: 17 December 2017.
Los Angeles Times, 2007. Hurricane Felix heading for Caribbean island of Aruba. Available from: http://articles.latimes.com/2007/sep/02/world/fg-storms2, Accessed date: 20 December 2017.
MacGregor, N., 2017. Vanuatu Feeling the Force of Severe Tropical Cyclone Donna. http://www.abc.net.au/news/2017-05-07/tropical-cyclone-donna-intensifies-to-category-four/8504140, Accessed date: 17 December 2017.
Masters, J., 2012. Category 3 Tropical Cyclone Evan Bearing Down on Fiji. https://maps.wunderground.com/blog/JeffMasters/comment.html?entrynum=2312&page=2, Accessed date: 16 December 2017.
Mauritius Meteorological Services, 2017. Historical Background. http://metservice.intnet.mu/about-us/historical-background/ (accessed 12.12.2017).
Meteo France, 2017. RMSC Archives. Details of the Archived Systems. http://www.meteo.fr/temps/domtom/La_Reunion/webcmrs9.0/anglais/index.html, Accessed date: 10 December 2017.
Ministry of Economy, 2017. 5-year and 20-year National Development Plan: Transforming Fiji. Republic of Fiji.
Mukoon, M.S., 2013. The mitigation of operational risks for the electricity utility in Mauritius. The Journal of the Institution of Engineers Mauritius 21–25.
NHC, 2017. Archives: Tropical Cyclone Reports. Atlantic Hurricane Season. . http://www.nhc.noaa.gov/data/tcr/index.php?season=2016&basin=atl, Accessed date: 20 December 2017.
O'Rourke, T.D., 2007. Critical infrastructure, interdependencies, and resilience. BRIDGE-Washington-National Academy of Engineering- 37 (1), 22.
OCHA, 2014. Comoros Islands: Cyclone Hellen. https://www.humanitarianresponse.info/sites/www.humanitarianresponse.info/files/Comoros_Hellen%20Impact_02_April_2014_OCHA_ROSA.pdf, Accessed date: 11 December 2017.
OECD/IEA, 2015. Making the Energy Sector More Resilient to Climate Change. COP 21.
Packham, C., Greenfield, C., 2017. Warning Lifted as Cyclone Shifts Away from New Caledonia. https://www.reuters.com/article/us-pacific-cyclone/warning-lifted-as-cyclone-shifts-away-from-new-caledonia-idUSKBN17D046, Accessed date: 17 December 2017.
Padgett, G., 2005. Monthly Global Tropical Cyclone Summary February 2005. http://australiasevereweather.com/cyclones/2005/summ0502.htm, Accessed date: 17 December 2017.
Pan African News Agency, 2002. Cyclone Dina Kills Five in Mauritius. https://reliefweb.int/report/mauritius/cyclone-dina-kills-five-mauritius, Accessed date: 10 December 2017.
Panapress, 2002. Le cyclone Dina cause des dégâts considérables à Maurice. http://www.panapress.com/Le-cyclone-Dina-cause-des-degats-considerables-a-Maurice–13-588746-17-lang4-index.html, Accessed date: 10 December 2017.
Park, J., Seager, T.P., Rao, P.S.C., Convertino, M., Linkov, I., 2013. Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Anal. 33 (3), 356–367.
Pasch, R.J., Kimberlain, T.B., 2011. Tropical Cyclone Report: Hurricane Tomas (AL212010). National Hurricane Center.
Phipps, C., 2017. Hurricane Maria: Dominica 'in Daze' after Storm Leaves Island Cut off from World. https://www.theguardian.com/world/2017/sep/21/dominica-daze-hurricane-maria-island-caribbean-rescue, Accessed date: 28 December 2017.
PIDP, 2016. 2 Years after Tonga Cyclone, Ha'apai Electrical Work Complete: Pacific Islands Report. . http://www.pireport.org/articles/2016/03/09/2-years-after-tonga-cyclone-ha%E2%80%98apai-electrical-work-complete, Accessed date: 16 December 2017.
Power Grid Corporation of India Ltd, 2015. Building Climate Change Resilience for Electricity Infrastructure.
Prasad, R.D., Bansal, R.C., Raturi, A., 2017. A review of Fiji's energy situation: challenges and strategies as a small island developing state. Renew. Sustain. Energy Rev. 75, 278–292. https://doi.org/10.1016/j.rser.2016.10.070.
Raphelson, S., 2017. 2 Months after Maria and Irma, U.S. Virgin Islands Remain in the Dark. https://www.npr.org/2017/11/14/564138720/2-months-after-maria-and-irma-u-s-virgin-islands-remain-in-the-dark, Accessed date: 28 December 2017.
Resnick, B., Barclay, E., 2017. What Every American Needs to Know about Puerto Rico's Hurricane Disaster. https://www.vox.com/science-and-health/2017/9/26/16365994/hurricane-maria-2017-puerto-rico-san-juan-humanitarian-disaster-electricty-fuel-flights-facts, Accessed date: 28 December 2017.
Schaeffer, R., Szklo, A.S., de Lucena, A.F.P., Borba, B.S.M.C., Nogueira, L.P.P., Fleming, F.P., Troccoli, A., Harrison, M., Boulahya, M.S., 2012. Energy sector vulnerability to climate change: a review. Energy 38 (1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056.
Shah, K.U., Niles, K., 2016. Energy policy in the Caribbean green economy context and the Institutional Analysis and Design (IAD) framework as a proposed tool for its development. Energy Pol. 98, 768–777. https://doi.org/10.1016/j.enpol.2016.07.045.
Shah, K.U., Rivera, J.E., 2007. Export processing zones and corporate environmental performance in emerging economies: the case of the oil, gas, and chemical sectors of Trinidad and Tobago. Pol. Sci. 40 (4), 265–285. 2007. https://doi.org/10.1007/s11077-007-9045-8.
Shah, K.U., Philippidis, G., Dulal, H.B., Brodnig, G., 2014. Developing biofuels industry in small economies: policy experiences and lessons from the Caribbean basin initiative. Mitig. Adapt. Strategies Glob. Change 19 (2), 229–253. https://doi.org/10.1007/s11027-012-9437-8.
Shah, K.U., Blechinger, P., Furlonge, H., Philippidis, G., Surroop, D., Singh, A., 2016. Special issue on energy policy for the future of small island developing states (SIDS). Energy Pol. 98, 650–652.
Shirley, R., Kammen, D., 2013. Renewable energy sector development in the Caribbean: current trends and lessons from history. Energy Pol. 57, 244–252. https://doi.org/10.1016/j.enpol.2013.01.049.
Statistics Mauritius, 2015. Historical Series: Energy and Water Statistics.
Statistics Mauritius, 2016. Digest of Environment Statistics 2015. Ministry of Finance and Economic Development, Republic of Mauritius.
Stewart, S.R., 2017. National Hurricane Center Tropical Cyclone Report: Hurricane Matthew (AL142016). NOAA and National Weather Services.
Stuff, 2016. Tonga Takes Stock after Cyclone Ula Creates Widespread Damage. https://www.stuff.co.nz/world/south-pacific/75600686/tonga-takes-stock-after-cyclone-ula-creates-widespread-damage, Accessed date: 16 December 2017.
Surroop, D., Raghoo, P., 2017. Energy landscape in Mauritius. Renew. Sustain. Energy Rev. 73, 688–694. https://doi.org/10.1016/j.rser.2017.01.175.
Surroop, D., Raghoo, P., Wolf, F., Shah, K.U., Jeetah, P., 2018. Energy access in small island developing states: status, barriers and policy measures. Environ. Develop In Press, Corrected Proof. https://doi.org/10.1016/j.envdev.2018.07.003.
The Telegraph, 2017. Hurricane Maria: Puerto Rico Left Entirely without Power. http://www.telegraph.co.uk/news/2017/09/20/hurricane-maria-path-latest-news-live-puerto-rico-virgin-islands/, Accessed date: 28 December 2017.
Timilsina, G.R., Shah, K.U., 2016. Filling the gaps: policy supports and interventions for scaling up renewable energy development in Small Island Developing States. Energy Pol. 98, 653–662. https://doi.org/10.1016/j.enpol.2016.02.028.
Uhlhorn, E., 2016. Winston, Fiji's Strongest Tropical Cyclone. http://www.air-worldwide.com/Blog/Winston,-Fiji-s-Strongest-Tropical-Cyclone/, Accessed date: 16 December 2017.
UN Office for the Coordination of Humanitarian Affairs, 2002. Mauritius-tropical Cyclone Dina OCHA Situation Report No. 4. . https://reliefweb.int/report/mauritius/mauritius-tropical-cyclone-dina-ocha-situation-report-no-4, Accessed date: 10 December 2017.
UN Office for the Coordination of Humanitarian Affairs, 2008. Hurricane Gustav OCHA Situation Report No. 4. . https://reliefweb.int/report/haiti/hurricane-gustav-ocha-situation-report-no-4, Accessed date: 21 December 2017.
UN Office for the Coordination of Humanitarian Affairs, 2010. Cook Islands: Tropical Cyclone Pat Situation Report No. 6. . https://reliefweb.int/report/cook-islands/cook-islands-tropical-cyclone-pat-situation-report-no-6, Accessed date: 17 December 2017.
UNDP, 2017. Samoa Is Ready to IMPRESS with Launch of Large-scale Renewable Energy Project. http://www.asia-pacific.undp.org/content/rbap/en/home/presscenter/pressreleases/2017/10/31/samoa-is-ready-to-impress-with-launch-of-large-scale-renewable-energy-project.html, Accessed date: 7 January 2018.
UNICEF, 2016. UNICEF Pacific Cyclone Winston Situation Report. Reporting Period 22-24 February 2016. Humanitarian Situation Report #2.
Union of Comoros and UNDP, 2012. Comoros Flash Floods: Joint Assessment Report.
United Nations University, 2016. World Risk Report.
Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, adaptability and transformability in social-ecological systems. Ecol. Soc. 9 (2).
Williams, J., 2015. Ten Years Ago, Hurricane Wilma Underwent Most Extreme Intensification in Atlantic History. https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/10/19/ten-years-ago-hurricane-wilma-underwent-most-extreme-intensification-in-atlantic-history/?utm_term=.cc7f4ced6549, Accessed date: 20 December 2017.
Wolf, F., Surroop, D., Singh, A., Leal, F., 2016. Energy access and security strategies in small island developing states. Energy Pol. 98, 663–673. https://doi.org/10.1016/j.enpol.2016.04.020.
World Bank, 2017a. World Development Indicators – the Little Green Data Book. Washington DC.
World Bank, 2017b. World Bank Approves US$35 Million for Clean Energy and Improved Electricity Access in Haiti. http://www.worldbank.org/en/news/press-release/2017/10/26/world-bank-approves-us35-million-for-clean-energy-and-improved-electricity-access-in-haiti, Accessed date: 7 January 2018.
World Health Organisation, 2010. Tonga Cyclone Situation Report 1. . https://reliefweb.int/report/tonga/tonga-cyclone-situation-report-1, Accessed date: 16 December 2017.
World Risk Report, 2017. World Risk Report - Analysis and Prospects 2017.